Developments in Fuel Cell Technologies in the Transport Sector. Current Challenges and Developments.

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Abstract

The demand for clean power source which can be used to run the various types of vehicles on the road is increasing on a daily basis due to the fact that high emissions released from internal combustion engine play a significant role in air pollution and climate change. Fuel cell devices, particularly Proton Exchange Membrane (PEM) type, are strong candidates to replace the internal combustion engines in the transport industry.

The PEMFC technology still has many challenges including high cost, low durability and hydrogen storage problems which limit the wide-world commercialization of this technology. In this paper, the fuel cell cost, durability and performances challenges which are associated with using of fuel cell technology for transport applications are detailed and reviewed. Recent developments that deal with the proposed challenges are reported. Furthermore, problems of hydrogen infrastructure and hydrogen storage in the fuel cell vehicle are discussed.

Keywords: fuel cell, PEM, cost, durability, hydrogen

1 INTRODUCTION

The transport sector is one of the major contributors of hazardous emissions to the environment in recent years. Many researches have been done on energy consumption analysis and fuel types were compared with each other including alternative fuel systems which are leading to more development in fuel technology [1]. This development can in turn reduce the oil consumption for transport [2]. There are two approaches in dealing with vehicle emissions problem. The first approach is the fuel type which can be addressed by either enhancing the quality of conventional fuel or by using alternative fuel systems. The second approach is upgrading the engine technology which includes in-use vehicles emission and the new vehicles emission standards.

In parallel with these developments; the transport sector has a good effect on a viable eco-driving strategy and reduction of excess fuel consumption [6- 7]. Achour et al. [8] developed a representative tool for the local authority in identifying the air quality caused by traffic emissions, in fact, many of these researches have to be applied in the developing countries as the transport sector is facing problems in oil supply [9]. Due to the growing global concerns on the depletion of petroleum based energy resources, and the environmental pollution and climate change caused by the burning of fossil fuels, renewable energy systems are suggested to play an increasing role in the transport sector year by year. Fuel cells have received an increased attention in recent years owing to their high efficiencies and low emissions.

A fuel cell is an electro-chemical power source which converts chemical energy in the form of fuel directly into electrical energy. However, unlike other electro-chemical power sources such as batteries which store their reactants within a cell, the reactants are fed continuously to it from external stores. Also, the electrodes in a fuel cell are not consumed as in a battery, irreversibly in a primary cell and reversibly in a secondary cell, and do not take part in the reaction. Fuel cells are already used to generate electricity for other applications, including in spacecraft and in stationary uses, such as emergency power generators.

Although the concept of a fuel cell was developed in England in the 1800s by Sir William Grove, the first workable fuels cells were not produced until much later, in the 1950s. During this time, interest in fuel cells increased, as NASA began searching for ways to generate power for space flights [13]. Several types of fuel cells are classified according to the electrolyte employed. The most popular type of fuel cells is the Proton exchange membrane fuel cells, also known as polymer electrolyte membrane (PEM) fuel cells (PEMFC). PEMFC use a solid polymer as an electrolyte and porous carbon electrodes usually containing a platinum or platinum alloy catalyst. They are typically fuelled with pure hydrogen supplied from storage tanks or reformers.

Hydrogen fuel is processed at the anode where electrons are separated from protons on the surface of a platinum-based catalyst. The protons pass through the membrane to the cathode side of the cell while the electrons travel in an external circuit, generating the electrical output of the cell. On the cathode side, another precious metal electrode combines the protons and electrons with oxygen to produce water, which is expelled as the only waste product; oxygen can be provided in a purified form, or extracted at the electrode directly from the air.

PEM fuel cells are used primarily for transportation applications and some stationary applications. Due to their fast start up time and favourable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses. Transport consumes about one quarter of the world total energy. In the case of internal combustion engines, a large part of the fuel energy is emitted as heat due to friction loss and exhaust gas.

In this paper, an overview of the proton exchange membrane fuel cell (PEMFC) was given. The application of the PEMFC in the transport market was displayed. The recent challenges and developments that are related to the cost, durability and performance, the hydrogen refulling infrastructure and the hydrogen storage in the vehicles are discussed.

2. The proton exchange fuel cell components

The main components of a single PEMFC power source (figure1) are, according to [23- 28]:

- Membrane Electrode Assembly (MEA) which consists of proton conducting electrolyte, cathode/anode porous electrodes, anodic/cathodic catalyst layers and gas diffusion layer. MEA is considered as the “heart” of the PEM fuel cell, because it is typically inserted by two flow field plates that are often mirrored to make a bipolar plate when cells are stacked in series for greater voltages.

- Anode/cathode current collectors with the reactant flow fields (also called bipolar plates). They act as electron conductors and they are in contact with the anode/cathode gas diffusers. The Bipolar Plates have the following functions to perform: to distribute the fuel and oxidant within the cell, to facilitate water management within the cell, to separate individual cells in the stack, to carry current away from the cell, and to facilitate heat management. For general transport applications, the graphite-based composite materials are best suited for Bipolar Plates as they offer excellent chemical resistance and good thermal and electrical conductivity combined with a lower density than metal plates. If strength is an additional criterion than only metal plates are a viable possibility.

- Auxiliaries that are needed for thermal and water management and for compression and transportation of gases (e.g. Anode/Cathode gas channel that supply the fuel cell with reactants).

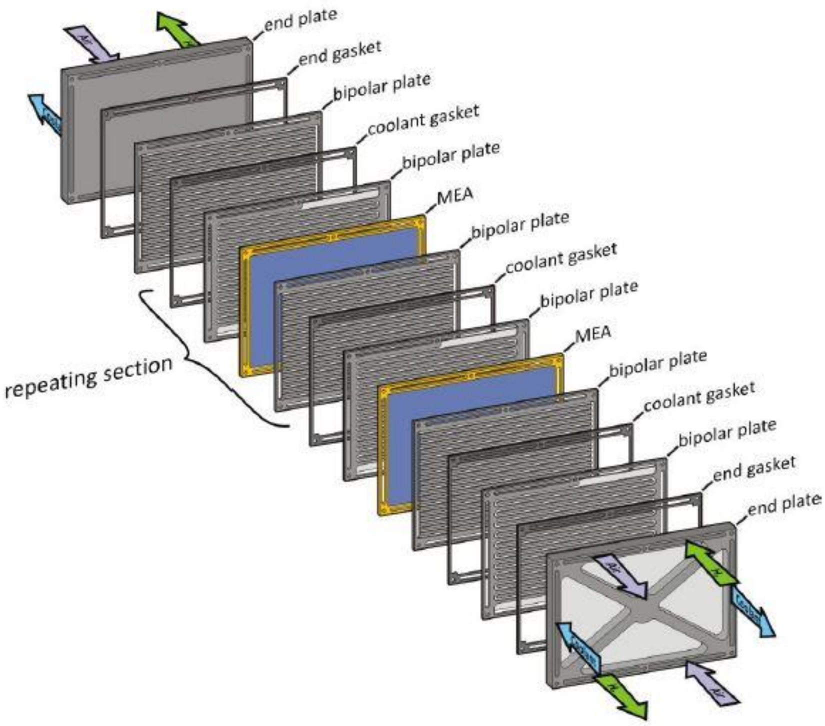

Fig 1: Main components of PEMFC stack [26]

In particular, the subcomponents of the MEA are very important to study from an economical point of view, especially the electrodes, because they represent the main contributors to the overall PEMFC stack cost. the current state-of-the-art of materials for fuel cells presents Nafion membranes for the electrolyte for low-temperature PEMFC (80°c) and h_3po_4–pbi membranes for high-temperature PEMFC (110°c-180°c), while for the electrodes and electro-catalysts platinum and platinum alloys are still the most preferred, even if they are still too expensive for the market and for the gas diffusion layers (GDL) the choice is for porous carbon cloth, or carbon paper, wet-proofed with a PTFE (Teflon) coating [28- 30]. A list of the most common materials for the PEMFC components is provided in table 1.

Table 1. Most common materials for a PEMFC stack.

Component	Functions	Most used materials	Other materials developed
Proton Exchange Membrane (PEM)	Charge carrier for protons	Nafion PBI	Sulfonated aromatic hydrocarbon polymer membranes
	Separate the reactant gases		Inorganic–organic composite membranes
	Electronic insulator		Polymer blend membranes
			Polybenzimidazole (PBI) based acid–base membranes

Electrodes and Catalyst Layers	Location of the half-cell reactions	Platinum	Pt electrodes with lower Pt content
		Platinum alloys	Total/partial substitution of Pt with other metals
Gas Diffusion Layers	Ensures that reactants effectively diffuse to the catalyst layer	Porous carbon	Continuous carbon-fiber based gas diffusion materials
	Electrical conductor for electrons to/from the catalyst layer	Paper or carbon cloth Teflon coating	
Bipolar Plates	Conduct current between cells	Graphite	Non-metals: non-porous graphite/electro graphite
	Facilitate water and thermal management through the cell		Metals: precious non coated metals, non-coated metals, coated metals
	Provide conduits for reactants		Composites: polymer–carbon and polymer–metal

3. Fuel cell in transportation

The transportation industry is one of the main important fields in the development of clean energy technologies. This is due to the fact that the transportation industry is responsible for 17% of the global greenhouse gas emissions every year [14], so that important changes are expected from this sector in order to reach the aims of Kyoto protocol [15]. The industry's outlook is to invest in technologies that would offer both significant reductions in harmful emissions and better energy conversion efficiencies.

Electric vehicles (EVs), which are driven by electrical energy stored in batteries or fuel cell units, are a potential option for reducing emissions from the transportation sector. EVs are proven to be significantly more efficient than internal combustion engines. Automobile manufacturers have been compelled to shift part of their production from internal combustion engines to (EVs) [13- 16]. The electrical motor converts more than 90% of the energy in its storage cells to motive force, whereas internal combustion drives use less than 25% of the energy in a gallon of gasoline. Additionally, in contrast with internal combustion engine, the electric motor can be directly connected to the wheels, so that no energy consumption is taken place when the car is at rest or freewheeling. Moreover, the regenerative braking system can return as much as half an electric vehicle's kinetic energy to the storage cells. On the other hand, EVs are considered to be more environmentally friendly than internal combustions vehicles [17- 18]. Combusting fossil fuels to power conventional vehicles releases GHG emissions and other pollutants from the vehicle exhaust system. In addition, there are also emissions associated with producing petroleum-based fuels, notably emissions from oil refineries. Electrical vehicles produce no GHG pollution when operating. However, it depends on how electrical energy is produced, there can be substantially lower upstream GHG emissions associated with producing hydrogen fuel. The important increase of the energy efficiency as long as the decrease of the vehicle weight in EVs over internal combustion vehicles are believed to have a significant effect on the GHG pollution reduction.

Electric vehicles can be powered either by batteries or by fuel cells. It has been stated that for any vehicle range greater than (100 miles), fuel cells are superior to batteries in terms of mass, volume, cost, initial greenhouse gas reduction, refuelling time, well-to-wheels energy efficiency using natural gas or biomass as the source and life cycle costs. However, hybridization of fuel cell systems with high specific energy-storage devices was found to have important advantages overcoming the relatively slow FCS transient response, improving the hydrogen economy and reducing the warm-up time of the FCS to reach full power. According to Carbon Trust, fuel cells could be powering up to 491 million cars by 2050 [19] – a third of all the cars on the road. In particular, the PEMFC technology can be ideally suited for transportation applications due to its high power density, high energy conversion efficiency, compactness, lightweight, and low-operating temperature. However, among all applications, for fuel cells the transportation application involves the most stringent requirements regarding volumetric and gravimetric power density, reliability, and costs. However, the high cost of this technology represents the biggest challenge for its commercialization.

Indeed, the fuel cell transportation applications can be specified into the following markets: auxiliary power units (APUs), light traction vehicles (LTVs), light- duty fuel cell electric vehicles (L-FCEVs), heavy-duty fuel cell electric vehicles (H-FCEVs), aerial propulsion, and marine propulsion. Light traction vehicles (LTVs) include scooters, personal wheel-chairs, motorbikes, airport tugs, golf carts, electric-assisted bicycles, etc. in addition to material handling vehicles and equipment (e.g. carts, wheel carts, forklifts, tow trucks, pallet trucks, etc). One of the most important future application in this field will be fuel cell-based motorcycle, because, even if they have a small size, motorcycles are a major source of pollution in cities [20]. Forklifts have been the most successful demonstration of fuel cells in the transportation sector, and one of the most successful demonstrations for fuel cells overall. Until now, for example, around 1300 fuel cell-powered forklifts are operative in the US market today. Due to their advantages, PEMFCs are the most popular fuel cells in light fuel cell electric vehicles (L-FCEVs) research and development [14]. The principle of how FCEVs work is simple; they use low temperature fuel cells (mainly PEM) to generate electricity from hydrogen, and then the electricity is used to drive the vehicle or stored in batteries or ultra-capacitors [21]. Since fuel cells generate electricity from chemical reactions, they do not combust fuel and therefore do not produce harmful emissions and produce much less heat than internal combustion engines. In fact, the only by-product of a hydrogen fuel cell is water.

There are a lot of car manufacturers which are increasingly progressing for the commercialization of L-FCEVs (e.g. General Motors, Toyota, Mazda, Daimler AG, Volvo, Volkswagen, Honda, Hyundai, Nissan) [14]. In 2007, the vehicle manufacturer Honda presented the model FCX Clarity at Los Angeles automobile saloon. This model is available for the consumer since the summer of 2008. This was the first fuel cell vehicle platform-exclusive in the world manufactured in series [20]. At the 2010 Fuel Cell Expo in Tokyo, Japanese automakers announced a programme designed to deploy 2 million FCEVs in Japan by 2025, at which point the industry estimates FCEVs would be fully competitive [21].

Heavy-duty fuel cell electric vehicles (H-FCEVs) include buses, heavy-duty trucks, locomotives, vans, utility trucks, service fleets, and other large load vehicles which use fuel cells for the electric propulsion system [14]. A number of fuel cell buses have been noted in operation worldwide during the last few years [20]. In 2012, more than 30 fuel cell buses in Western Europe, and other 25 in the United States were deployed. Fuel cell electric buses (FCEBs) are becoming one of the best public demonstration tools and R&D data sources in the H-FCEVs industry. PEMFCs are the most commonly-used types of fuel cells stacks used in the transportation, taking the advantages of regenerative braking energy recovery and high dynamic response performance. However, the immaturity of fuel cell technologies and the lack of mass production and manufacturing are making FCEBs economically-uncompetitive with conventional buses and other competing arising technologies.

Fuel cells application in marine transportation is increasing during the last years. Potential use of fuel cells as auxiliary power units on surface ships, is becoming an actual chance and probably in the future fuel cell systems will share with diesel engines the marine propulsion task. Promising future marine propulsion markets for fuel cells include ferries, boats, yachts, and cargo ships, but mostly submarines and underwater vehicles [22]. Fuel cells offer their regular advantages for ships and ferries, such as low emissions, high efficiency, and static operation, but they have also issues related to reliability, lifetime, shock resistance, and tolerance to the salt content of sea air which have to be resolved [14]. Therefore, according to [22], marine applications of fuel cells are not so developed as in other transport sectors such as automotive or aerial propulsion. Fuel cell technology, so far, does not assure a clear improvement in the respect of certain requirements of space taken (volume) and weight which are required for a ship. Moreover, the marine environment is very hostile especially with regard to dynamic loads and the high corrosion. The application of fuel cell technology in this field needs to be adapted to these circumstances in order to operate normally with a required life cycle. There is a lack of infrastructure to facilitate the commercialization of this technology and, in general, the price of the energy generated by fuel cells is still higher than the ones obtained by internal combustion engines conventional systems.

On the other hand, in 2003, the first yacht with a hybrid PEMFCs/batteries system for both propulsion and auxiliary power unit as demonstrated in Germany and, also in Germany, the world's first commercial passenger-ship was put into service in 2008. Submarines that use oxygen/hydrogen fuel cells for propulsion and auxiliary load requirements have also been successfully deployed. PEMFC are the main technology considered to provide a new generation of conventional submarines with an Air Independent Propulsion system (AIP) through Germany, Greece, Italy, Portugal and Spain [22].

The space industry was one of the first fields to adopt fuel cells in. NASA used alkaline fuel cells (AFC)s and PEMFCs technologies for its manned space programs during the 1960s. Fuel cells are attractive for space applications due to their many advantaged compared to other power generation technologies. However, the fact that water is a by-product of the electrochemical reactions within a fuel cell makes it even more attractive for space applications where air, water, and food supplies are of most importance. On the other hand, the market of manned military and commercial air vehicles is still impractical for fuel cells due to the market's high energy density, power density, durability, and reliability requirements, especially for the development of small unmanned aerial vehicles (UAVs). The stealth nature of UAVs is facilitated by fuel cells' static operation, and low heat dissipation that represents together two advantages over UAVs with internal combustion engines. UAVs are mainly used for surveying, surveillance, and reconnaissance purposes due to their stealth nature and lack of risk to human life [14].

4 CURRENT CHALLENGES AND DEVELOPMENTS

Fuel cell technology is showing year-on-year growth, with more prototypes being unveiled. Successful application of these technologies in the transport sector has taken place in Europe and USA. However, the fuel cell industry is still facing a number of challenges to commercialization. Fuel cell cost is one major challenge, the durability of the unit and its performance is another important one. The challenge of hydrogen infrastructure and storage is essential for the technology wide spread in transportation.

4.1. Fuel Cell Cost

Fuel cell costs can be broken into three elements: the material and component costs, labor (design and fabrication), and capital cost of the manufacturing equipment [31, 32]. It is clearly seen that labor and capital costs can be reduced through mass-manufacturing. Material and component costs, such as catalysts, membrane and bipolar plates, are dependent on technological innovations and the market [33, 34]. According to Carbon Trust, in order to be competitive with internal combustion engine vehicles, automotive fuel cells must reach approximately $36/kW. Platinum (Pt) is a precious metal, with around 250 tonnes annually production. It is currently mined in South Africa, Russia and North America. Estimated world reserves of Pt are >30,000 tonnes. Given its high value, the majority of Pt used in FCEVs is likely to be recycled at the end of life of the vehicle.

Cost savings can be achieved by reducing material costs (in particular: platinum use), increasing power density, reducing system complexity and improving durability. Reducing the amount of platinum in the electro-catalyst layer will reduce the overall cost of the PEMFC technology and allow for mass production particularly in transport applications. Mainly, the platinum content can be reduced either by using Pt-alloy catalysts or by the application of core shell catalysts. The Pt-alloy catalysts [35- 36] mean alloying platinum with low cost metals such as ruthenium (Ru) or chromium (Cr). The core shell catalysts [37] are nanoscopic low cost metal core such as Copper (Cu) and rhenium (Rh) covered by a platinum shell. Platinum content of fuel cells was reduced by more than doubling catalyst specific power from the 2008 baseline of 2.8 kW/g of platinum group metal (PGM) to 5.8 kW/g in 2012. Current catalyst specific power is approaching the 2017 target of 8.0 kW/g, and it reflects more than 80 percent reduction in PGM content since 2005. Several UK organisations are focused on achieving a step-change in PEM fuel cell system costs, by developing technologies that reduce platinum use, increase power densities and radically simplify system designs.

Developing of Platinum-free catalysts is another route to reduce the cost of the fuel cell. In this route, active metals such as Cobalt (Co) and Iron (Fe) were used as alternative to Platinum in the catalysts of PEMFC technology. ACAL Energy’s patented FlowCath® [23, 38] fuel cell design uses a liquid polymer cathode solution, which replaces the platinum-based solid cathode used in standard PEM fuel cells. This represents a fundamental design breakthrough that has the potential to reduce expensive platinum use by at least two thirds, reduce the number of components within the overall system (by avoiding fuel humidification and water recovery), and increase durability (as it replaces the solid cathode of typical systems, which usually suffers performance degradation that limits product lifetime). The projected fuel cell cost given for the FlowCath® fuel cell was 36 $/kW.

Another patent [39, 23] was made by ITM Power's to demonstrate exceptional high power densities by replacing the perfluorosulfonic acid membranes that are the current industry standard with a membrane fabricated by ionic polymers. Higher power densities translate into more power per cell; hence a much smaller, lighter, and cheaper stack can meet the same power output. The proposed fuel cell cost given for by ITM Power's fuel cell was 35 $/kW.

In a further patent, fuel cell stack design was improved by Imperial College & University College London [23]. The so called 'Flexi- Planar' design uses a layered arrangement of laminated, printed circuit board materials, bonded on top of each other to create a fuel cell stack with internal fuel, water and air channels. These boards lead to cost benefits over conventional fuel cell systems by eliminating the need for several components that are normally used in a conventional fuel cell. The biggest areas for potential cost reduction are air-, fuel- and water-management, sealing (no gaskets or frame required) and stack assembly. The planned cost of the proposed fuel cell according to this project is 26 $/kW.

4.2. Durability and performances

Both low durability and reliability are caused by accumulated degradation of materials and catalyst due to water and heat issues [24, 40]. The degradation of materials and catalyst are mainly because of poor water management, fuel and oxidant starvation, corrosion and chemical reactions of cell components that cause dehydration or flooding. The dehydration can damage the membrane and flooding can facilitate corrosion of the electrodes, the catalyst layers, the gas diffusion media and the membrane. Lifetime of fuel cells can be extended either by controlling the flow conditions (i.e. humidity, flow rates and temperature) or by changing the materials and the flow design.

One of these strategies that meant to enhance the mechanical durability of the PEM fuel cell is to design and develop cheap bipolar plate with high corrosion resistance. Traditionally, graphite was used to fabricate the bipolar plates, because of its high corrosion resistance, relatively low surface contact resistance and high surface conductivity, in the PEM fuel cell environment. However, graphite is brittle and thus it is not suitable for transport application where a lot of vibrations and loading are occurred. Metals, metals alloys, and carbon based composites have been suggested recently to develop cost-effective and durable bipolar plates which can replace the graphite ones. In fact, metals and their alloys provide several advantages over the carbon-based composites for fuel cells used in transport application as they possess higher mechanical strength and can be made thinner to achieve higher power density better durability [41]. Generally, it was found that bare metals such SS, Al, Ti, Ni, etc. are prone to corrosion in the PEM fuel cell environment [42]. The corrosion behaviour of metallic flow plates causes many undesirable phenomena such as increasing the electrical resistance and decreasing the efficiency and power output of the fuel cell [41, 43- 44]. Thus, Corrosion resistant coatings are required to avoid the corrosion problem in the metallic bipolar plates. Two main classifications of coatings, carbon-based and metal-based, have been studied [45]. Carbon-based coatings include conductive polymers (e.g., polyaniline (PANI) and polypyrrole (PPY)) [46], graphite [47] and Composite coating (e.g., TiC-ETFE, Ag-PTFE) [48- 49]. The metal-base coatings for bipolar plate applications include Noble metals [50], metal nitrides [51- 53], and metal carbides [54- 55], and conductive metal oxide (e.g., fluorine doped Tin (II) oxide (SnO2: F) and Ruthenium oxide (RuO2)) [56- 57].

On another hand, the carbon corrosion in the catalyst layer was considered as a major degradation source in operating a PEM fuel cell. It is well known that Platinum nanoparticles supported on carbon black (Pt/C) were found the most promising electrocalyast applied on PEMFC. However, platinum nanoparticles in catalyst layers must have simultaneous access to the gases, electrons, and protons to be effectively utilized. When operating under extremely high current conditions, platinum nanoparticles in the thin catalyst layers may detach from the support carbon and accelerate the degradation of the electrochemical performance. It was found that mixing of graphene with conventional Pt/C was able to transport electrons effectively and to provide better pathways under high current density conditions [58]. Graphene displays low electrical resistance and provides channels with better conductivity for large amount of electrons. Graphene can potentially provide much higher durability than carbon black with its unique graphitized basal plane [59].

Some minimum level of hydration is required to facilitate efficient ionic conductivity in the proton exchange membrane. However, excess hydration will be related to reliability issues such as voltage loss at high current density, voltage instability at low current density, unreliable start-up under freezing conditions, and will promote the corrosion of the carbon in the catalyst support due to hydrogen starvation [60]. Therefore, the design of membrane and its material selection must comprehend the critical balance between too little and too much hydration, especially for automotive applications where the fuel cell can be subjected to wide variations in load demand and ambient conditions during its lifetime. Another approach is to develop the proton exchange membranes to improve the performance and durability of the standard membranes made of Nafion. However, in spite of their high proton conductivities and fuel cell performances, sulfonated statistical copolymers are generally characterized by a high degree of dimensional change and poor durability derived from a poorly connected non-hydrated phase and inordinate dimensional variation in the hydrated phase. Alternatively, The sPP-b-PAES(6.5K)-3.0 membrane had been developed by [61]. The developed membrane showed high proton conductivity, stable dimensional variation, along with high performance and durability superior to those of Nafion.

In June 2013, ACAL Energy Ltd [58] announced that it enabled a PEM hydrogen fuel cell to reach 10,000 hours runtime on a third party automotive industry durability test without any significant signs of degradation. 10,000 hours, the equivalent of 300,000 driven miles, is the point at which hydrogen fuel cell endurance is comparable to the best light-weight diesel engines under such test conditions. This endurance far exceeds the current 2017 US Department of Energy (DoE) industry target for fuel cell powered vehicles to last 5,000 hours, equivalent to 150,000 road miles, with an expected degradation threshold of approximately 10%. Unlike a conventional PEM hydrogen fuel cell design, ACAL Energy's technology does not rely on platinum as the catalyst for the reaction between oxygen and hydrogen. The liquid acts as both a coolant and catalyst for the cell's, ensuring that they last longer by removing most of the known decay mechanisms.

4.3.Hydrogen refuelling infrastructure:

Hydrogen is the lightest chemical element and it has the lowest storage density of all fuels. Historically, the H2 fuelling infrastructure has been technically infeasible and too expensive. Sales of fuel cell vehicles are clearly dependent on the existence of the hydrogen infrastructure required for fuel [62]. The extensive system used to deliver gasoline from refineries to local filling stations cannot be used for hydrogen. New facilities and systems must be constructed for producing, transporting, and dispensing hydrogen to consumers [63]. At present, industry experts are focusing on supply chains, H2 compression, high pressure storage components, and standardizing station designs as the primary approach to reducing station costs. All hydrogen refuelling infrastructure consists of the following components (Hydrogen supply, Hydrogen storage, and the Hydrogen refueller).

Two options are given for Hydrogen supply. Either Hydrogen is delivered to the site or it can be generated on-site [64]. Delivered hydrogen can exist either in a liquefied form by tanker truck, or as a compressed gas in cylinders. Liquefied hydrogen tends only to be delivered in large volumes whereas compressed gas is far more scalable and can be supplied in small quantities. On the other hand, on-site hydrogen generation can be taken place mainly either by reformation of natural gas (a process of splitting methane into molecules of hydrogen and carbon dioxide), or by electrolysis of water (using electrical current to split water into hydrogen and oxygen). Currently, most hydrogen is produced from natural gas reformation. In longer term, solar energy and biomass can be used more directly to generate hydrogen.

Hydrogen storage system depends on the hydrogen form. If hydrogen is delivered as a liquid, a cryogenic storage vessel will be required on the site to maintain the temperature in the liquid range. When hydrogen is delivered as a compressed gas, the storage vessel is usually dropped off at the site by a truck and then replaced when empty. If hydrogen is generated on-site, it will be transferred from the reformer or electrolyser via a compressor to a compressed storage vessel. Liquefaction of hydrogen is an energy intensive process requiring large plant and would only be considered at a location where very large quantities of hydrogen were being produced. Hydrogen refueller delivers hydrogen to the vehicle's tank in a controlled manner and to the correct pressure [65, 66]. Hydrogen is dispensed to the vehicle through a flexible hose and nozzle connected to the vehicle's tank, in a similar fashion to refilling with petrol or diesel. However, it has been noticed that the infrastructure requirement and financial resources allocated for the production and supply of oil and natural gas were enormous during the initial several decades of commercialisation efforts of this sector. It was more of a politico-economic policy and funding which brought oil and natural gas to its present state. Hence, it will require a huge initiative for replicating the same for hydrogen in the near future and the Governments of various countries must align their requirement of energy for the future in terms of increasing the usage of hydrogen as a transport fuel [67].

4.4. Hydrogen storage in vehicles:

The cruising range of vehicle is limited by the amount of hydrogen on board. It has only 1/10 of energy compared with gasoline from the same volume. Therefore, it is necessary to increase both storable hydrogen and efficiency to achieve comparable range as gasoline vehicles. Some Fuel Cell Vehicles (FCVs) store enough hydrogen to travel as far as gasoline vehicles between fill-ups—about 300 miles—but the storage systems are still too large, heavy, and expensive [64, 66].

Three practical ways were offered for Hydrogen storage on the FCVs. One of them is storing hydrogen gas in high pressure tanks which is the current hydrogen storage system in FCVs. This system is different from the compressed natural gas vehicle because the hydrogen vehicle uses higher pressure than the natural gas vehicle, which is normally compressed to 20–25 MPa.

Recently there is a trend to move to 70 MPa tank to carry more hydrogen in order to extend vehicle range. However, these systems are still heavy, large and costly. Moreover, it is well known that hydrogen diffuses more easily through many conventional materials used for vessels, and through gaps that are normally small enough to seal other gases safely [68]. The currently validated high-pressure tank technology is close to meeting the revised DOE 2017 target 5.5% of system gravimetric capacity and 40 g/l of system volumetric capacity. It utilizes expensive premium carbon reinforcement to meet the challenging structural requirement of supporting over 150 MPa burst pressure as specified in current regulations. However, using tank technology, it is impossible to reach the ultimate DOE targets of 7.5% gravimetric capacity and 70 g/l volumetric capacity of the storage system [68].

Another storing system is using hydrogen in the liquid form by cooling the hydrogen gas to 20 K at the atmospheric pressure. Storage systems using liquid hydrogen have the potential of storing a larger amount of hydrogen on board than when using high pressure tanks, but it needs tanks with double wall construction to keep the low temperature with the thermal insulation [62]. The third storage system is the materials based storage in which hydrogen is stored in solid form, it can be absorbed in high density by different absorbing alloys. Such alloys are smaller and lighter than tanks in other methods. The hydrogen is released from these compounds by heating or the addition of water. More research is needed in this area to develop these materials [69]. Application of Metal Organic Frameworks (MOFs) for hydrogen storage applications gained a high attention due to their huge structural diversity, ability to tune the pore size and surface functionality, exceptional porosity and surface area, and their rich chemistry. However, despite the rapid progress in metal organic frameworks (MOF)s research, these materials still doesn’t comply with DOE targets [70].

5 Summary

This paper highlighted the main challenges associated with using the PEM fuel cell for transport applications. PEMFC provides several advantages over the traditional internal combustion engine, which are the formal power source in transport industry, including higher efficiency and lower emissions.

Latest developments that aim to approach the planned targets and to break the commercialization barriers of the PEMFC technology were also reported.

However, to meet the full requirements as power sources for transport applications, the fuel cell researchers have to overcome serious challenges related to high cost, low durability, hydrogen refulling infrastructure and hydrogen storage on the fuel cell vehicles (FCVs).

References:

[1] Ou, X., Yan, X., Zhang, X. and Liu, Z. 2012. Life-cycle analysis on energy consumption and GHG emission intensities of alternative vehicle fuels in China. Applied Energy, 90(1), pp.218-224.

[2] Han Hao, Hewu Wang, Lingjun Song, Xihao Li, Minggao Ouyang, Energy consumption and GHG emissions of GTL fuel by LCA: Results from eight demonstration transit buses in Beijing, Applied Energy, Volume 87, Issue 10, October 2010, Pages 3212-3217, ISSN 0306-2619, DOI: 10.1016/j.apenergy.2010.03.029.

[3] B. Saerens, J. Vandersteen, T. Persoons, J. Swevers, M. Diehl, E. Van den Bulck, Minimization of the fuel consumption of a gasoline engine using dynamic optimization, Applied Energy, Volume 86, Issue 9, September 2009, Pages 1582-1588, ISSN 0306-2619, DOI: 10.1016/j.apenergy.2008.12.022.

[4] Arteconi, A., et al., (2010), "Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe", Appl.Energy, Vol.87 (6), pp. 2005-2013.

[5] Jose M Lopez, Alvaro Gomez, Francisco Aparicio, Fco. Javier Sanchez, Comparison of GHG emissions from diesel, biodiesel and natural gas refuse trucks of the City of Madrid, Applied Energy, Volume 86, Issue 5, May 2009, Pages 610-615, ISSN 0306-2619, DOI: 10.1016/j.apenergy.2008.08.018.

[6] Y. Saboohi, H. Farzaneh, Model for developing an eco-driving strategy of a passenger vehicle based on the least fuel consumption, Applied Energy, Volume 86, Issue 10, October 2009, Pages 1925-1932, ISSN 0306-2619, DOI: 10.1016/j.apenergy.2008.12.017.

[7] H. Achour, A.G. Olabi, Driving Cycle Developments And Their Impacts On Energy Consumption Of Transportation, Journal of Cleaner Production, Available online 11 August 2015, ISSN 0959-6526.

[8] H. Achour, J.G. Carton, A.G. Olabi, ‘Estimating vehicle emissions from road transport, case study: Dublin City’, Applied Energy, Volume 88, Issue 5, May 2011, Pages 1957-1964.

[9] H. Achour, A. Marashly, A. G. Olabi, (2012), "Assessing Energy Consumption of the Transport Sector in Aleppo, SYRIA", Journal of Sustainable Manufacturing and Renewable Energy. Vol. 1 Issue 3-4, pp 87-102.

[10] Lindfeldt, E.G., et al., (2010), "Strategies for a road transport system based on renewable resources – The case of an import-independent Sweden in 2025", Appl.Energy, Vol.87 (6), pp. 1836-1845.

[11] 100% renewable energy systems, climate mitigation and economic growth, Applied Energy. Volume 88, Issue 2, February 2011, Pages 488–501.

[12] Ayoub, K. 2003. Introduction of PEM fuel-cell vehicles in the transportation sector of the United Arab Emirates. Applied Energy, 74(1-2), pp.125-133.

[13] US DOD, Fuel Cell Test and Evaluation Center. History." http://www.fctec.com/fctec_history.asp. Accessed 31 December 2010.

[14] Omar Z. Sharaf, Mehmet F. Orhan, *An overview of fuel cell technology : Fundamentals and applications*, 13th February 2014

[15] G. Cacciola, V. Antonucci, S. Freni, *Technology up date and new strategies on fuel cells*, 2001

[16] LI Bing, LI Hui, MA Jianxin, WANG Haijiang. PEM Fuel Cells: Current Status and Challenges for Electrical Vehicle Applications. J Automotive Safety and Energy, 2010, Vol. 1 No. 4.

[17] Hofman P, Elzen B, Geels F. Sociotechnical scenarios as a new tool to explore system innovations: Co-evolution of technology and society in the Netherlands energy system [J]. Innov Manag Policy Pract, 2004, 6: 344-360.

[18] Elzen B, Geels F W, Hofman P S, et al. Sociotechnical scenarios as a tool for transition policy: An example from the traffic and transport domain [C]// Evidence and Policy, Edward Elgar, Cheltenham, 2004: 19-47.

[19] Polymer Fuel Cells – Cost reduction and market potential. A report by the Carbon Trust based on independent analysis September 2012. Carbon Trust.

[20] J.M. Andu´ jar, F. Segura, *Fuel cells: History and updating. A walk along two centuries*, 25th March 2009

[21] Bruno G. Pollet , Iain Staffell, Jin Lei Shang, *Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects*, 12th April 2012

[22] T.J. Leo a, J.A. Durango a, E. Navarro, *Exergy analysis of PEM fuel cells for marine applications,* 12th July 2009

[23] Paola Costamagna, Supramaniam Srinivasan, *Quantum jumps in the PEMFC science and technology from the 1960s to the year 2000 Part I. Fundamental scientific aspect,* 27th April 2001

[24] Atilla Bıyıkoglu, *Review of proton exchange membrane fuel cell models,* 6th July 2005

[25] S. Litster, G. McLean, *PEM fuel cell electrodes,* 14th December 2003

[26] Brian D. James, Jeffrey A. Kalinoski and Kevin Baum, *Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell System for Automotive Applications:2009 update,* 1st January 2010

[27] Allen Hermann, Tapas Chaudhuria, Priscila Spagnol, *Bipolar plates forPEMfuel cells:Areview,* 2nd June 2005

[28] H. Tawfik, Y. Hung, D. Mahajan, *Metal bipolar plates for PEM fuel cell—A review,* 20th November 2006

[29] Nonhlanhla P. Cele, Suprakas Sinha-Ray, Josiah Munda, disa A. Jimoh, *The State of the Art Proton Exchange Membrane Fuel Cells for Clean Energy,* 2010

[30] Alireza Khaligh, Zhihao Li, *Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art,* 6th July 2010

[31] Barriers of scaling-up fuel cells: Cost, durability and reliability. Junye Wang. Energy 80 (2015) 509-521.

[32] Marcinkoski J, James BD, Kalinoski JA, Podolski W, Benjamin T, Kopasz J. Manufacturing process assumptions used in fuel cell system cost analyses. J Power Sources 2011;196(12):5282e92.

[33] Odeh AO, Osifo P, Noemagus H. Chitosan: a low cost material for the production of membrane for use in PEMFCea review. Energy Sources, Part A: Recovery, Util Environ Eff 2013;35(2):152e63.

[34] Sun Y, Delucchi M, Ogden J. The impact of widespread deployment of fuel cell vehicles on platinum demand and price. Int J Hydrogen Energy 2011;36(17):11116e27.

[35] H. A. Gasteiger, N. Markovic, P. N. Ross, and E. J. Cairns, “Methanol electrooxidation on well-characterized platinum-ruthenium bulk alloys,” *J. Phys. Chem.*, vol. 97, no. 46, pp. 12020–12029, Nov. 1993.

[36] J. W. Long, R. M. Stroud, K. E. Swider-Lyons, and D. R. Rolison, “How To Make Electrocatalysts More Active for Direct Methanol OxidationAvoid PtRu Bimetallic Alloys!,” *J. Phys. Chem. B*, vol. 104, no. 42, pp. 9772–9776, Oct. 2000.

[37] K. S. Nagabhushana, C. Weidenthaler, S. Hocevar, D. Strmcnik, M. Gaberscek, A. L. Antozzi, and G. N. Martelli, “Preparation, Characterization and Properties of Pt-Cu Co-reduced and Pt-on-Cu Skin Type Bimetallic Carbon-Supported (Vulcan XC72) Electrocatalysts,” *J. New Mater. Electrochem. Syst.*, vol. 9, no. 2, p. 73, 2006.

[38] ACAL Energy News. Hydrogen fuel cell that’s as durable as a conventional engine. http://www.acalenergy.co.uk/news/release/acal-energy-system-breaks-the-10000-hour-endurance-barrier/en

[39] Fuel cell membrane performance update. ITM Power. http://www.itm-power.com/news-item/fuel-cell-membrane-performance-update

[40] Bae SJ, Kim S-J, Lee J-H, Song I, Kim N-I, Seo Y, et al. Degradation pattern prediction of a polymer electrolyte membrane fuel cell stack with series reliability structure via durability data of single cells. Appl Energy 2014;131: 48- 55.

[41] H. Wang, “Stainless steel as bipolar plate material for polymer electrolyte membrane fuel cells,” *J. Power Sources*, vol. 115, no. 2, pp. 243–251, Apr. 2003.

[42] A. HERMANN, T. CHAUDHURI, and P. SPAGNOL, “Bipolar plates for PEM fuel cells: A review,” *Int. J. Hydrogen Energy*, vol. 30, no. 12, pp. 1297–1302, Sep. 2005.

[43] A. Pozio, R. F. Silva, M. De Francesco, and L. Giorgi, “Nafion degradation in PEFCs from end plate iron contamination,” *Electrochim. Acta*, vol. 48, no. 11, pp. 1543–1549, May 2003.

[44] R. A. Antunes, M. C. L. Oliveira, G. Ett, and V. Ett, “Corrosion of metal bipolar plates for PEM fuel cells: A review,” *Int. J. Hydrogen Energy*, vol. 35, no. 8, pp. 3632–3647, Apr. 2010.

[45] V. Mehta and J. S. Cooper, “Review and analysis of PEM fuel cell design and manufacturing,” *J. Power Sources*, vol. 114, no. 1, pp. 32–53, Feb. 2003.

[46] S. JOSEPH, J. MCCLURE, R. CHIANELLI, P. PICH, and P. SEBASTIAN, "Conducting polymer-coated stainless steel bipolar plates for proton exchange membrane fuel cells (PEMFC)," *Int. J. Hydrogen Energy*, vol. 30, no. 12, pp. 1339–1344, Sep. 2005.

[47] Y. Show, "Electrically conductive amorphous carbon coating on metal bipolar plates for PEFC," *Surf. Coatings Technol.*, vol. 202, no. 4–7, pp. 1252–1255, Dec. 2007.

[48] J. R. Mawdsley, J. D. Carter, X. Wang, S. Niyogi, C. Q. Fan, R. Koc, and G. Osterhout, "Composite-coated aluminum bipolar plates for PEM fuel cells," *J. Power Sources*, vol. 231, pp. 106–112, Jun. 2013.

[49] Y. Fu, M. Hou, H. Xu, Z. Hou, P. Ming, Z. Shao, and B. Yi, "Ag–polytetrafluoroethylene composite coating on stainless steel as bipolar plate of proton exchange membrane fuel cell," *J. Power Sources*, vol. 182, no. 2, pp. 580–584, Aug. 2008.

[50] P. L. Hentall, J. B. Lakeman, G. O. Mepsted, P. L. Adcock, and J. M. Moore, "New materials for polymer electrolyte membrane fuel cell current collectors," *J. Power Sources*, vol. 80, no. 1–2, pp. 235–241, Jul. 1999.

[51] L. Zhang, L. Duan, Z. Guo, J. Wang, K. Zhao, W. . Tuan, and D. Niihara, "TiN-coated titanium as the bipolar plate for PEMFC by multi-arc ion plating.," *Int J Hydrog. Energy*, vol. 36 SRC - G, pp. 9155–9161, 2011.

[52] Z. Ren, D. Zhang, and Z. Wang, "Stacks with TiN/titanium as the bipolar plate for PEMFCs," *Energy*, vol. 48, no. 1, pp. 577–581, Dec. 2012.

[53] E. A. Cho, U.-S. Jeon, S.-A. Hong, I.-H. Oh, and S.-G. Kang, "Performance of a 1kW-class PEMFC stack using TiN-coated 316 stainless steel bipolar plates," *J. Power Sources*, vol. 142, no. 1–2, pp. 177–183, Mar. 2005.

[54] Y. Hung, H. Tawfik, and D. Mahajan, "Durability and characterization studies of polymer electrolyte membrane fuel cell's coated aluminum bipolar plates and membrane electrode assembly," *J. Power Sources*, vol. 186, no. 1, pp. 123–127, Jan. 2009.

[55] L. Yang, H. Yu, L. Jiang, L. Zhu, X. Jian, and Z. Wang, "Improved anticorrosion properties and electrical conductivity of 316L stainless steel as bipolar plate for proton exchange membrane fuel cell by lower temperature chromizing treatment," *J. Power Sources*, vol. 195, no. 9, pp. 2810–2814, May 2010.

[56] H. Wang and J. A. Turner, "SnO2:F coated ferritic stainless steels for PEM fuel cell bipolar plates," *J. Power Sources*, vol. 170, no. 2, pp. 387–394, Jul. 2007.

[57] H. Wang, J. A. Turner, X. Li, and R. Bhattacharya, “SnO2:F coated austenite stainless steels for PEM fuel cell bipolar plates,” *J. Power Sources*, vol. 171, no. 2, pp. 567–574, Sep. 2007.

[58] U.S. Department of Energy. Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program. September 2011.

[59] Graphene for energy conversion and storage in fuel cells and supercapacitors. Hyun-Jung Choi, Sun-Min Jung, Jeong-Min Seo, Dong Wook Chang, Liming Dai, Jong-Beom Baek. Nano Energy (2012) 1, 534–551.

[60] Jon P. Owejan, Jeffrey J. Gagliardo, Jacqueline M. Sergi and Thomas A. Trabold. Two phase flow consideration in PEMFC design and operation. Proceedings of the Sixth International ASME Conference on Nanochannels, Microchannels and Minichannels ICNMM2008 June 23-25, 2008, Darmstadt, Germany.

[61] Jang Yong Lee, Duk Man Yu, Tae-Ho Kim, Sang Jun Yoon, Young Taik Hong. Multi-block copolymers based on poly(p-phenylene)s with excellent durability and fuel cell performance. Journal of Membrane Science 492 (2015) 209–219.

[62] HYDROGEN PRODUCTION R&D: PRIORITIES AND GAPS Trygve Riis and Elisabet F. Hagen Preben J. S. Vie and Oystein Ulleberg. IEA PUBLICATIONS 9, rue de la Fédération, 75739 Paris Cedex 15 Printed in France by Stedi Média January 2006.

[63] Potential for Hydrogen as a Fuel for Transport in the Long Term (2020 - 2030) - Full Background Report - Matthias Altmann Patrick Schmidt Reinhold Wurster Martin Zerta Dr. Werner Zittel (Edited by Hector Hernandez). EUR 21090 EN

[64] Implementing a Hydrogen Energy Infrastructure: Storage Options and System Design Joan M. Ogden Christopher Yang. Institute of Transportation Studies ◊ University of California, Davis. 2005.

[65] Hydrogen resources. The Office of Energy Efficiency and Renewable Energy (EERE). Available online: http://energy.gov/eere/fuelcells/hydrogen-resources

[66] Hydrogen Refuelling & Storage Infrastructure. Information Resource for Highlands & Islands Enterprise. Available online: http://www.hi-energy.org.uk/Downloads/Hydrogen%20Fuel%20Cell%20Resource/3b-Hydrogen%20refuelling%20and%20storage%20infrastructure.pdf

[67] Hydrogen: A sustainable fuel for future of the transport sector. Sonal Singh, Shikha Jain, Venkateswaran PS, Avanish K. Tiwari, Mansa R. Nouni, Jitendra K. Pandey, Sanket Goel. Renewable and Sustainable Energy Reviews 51 (2015) 623–633.

[68] Introduction to hydrogen storage N.T. Stetson, S. McWhorter, C.C. Ahn. Compendium of Hydrogen Energy. http://dx.doi.org/10.1016/B978-1-78242-362-1.00001-8 2016 Published by Elsevier Ltd.

[69] Other methods for the physical storage of hydrogen. N.K. Zhevago. Compendium of Hydrogen Energy. http://dx.doi.org/10.1016/B978-1-78242-362-1.00008-0 Copyright © 2016 Elsevier Ltd. All rights reserved.

[70] Metal–organic frameworks for hydrogen storage H.W. Langmi, J. Ren, N.M. Musyoka. Compendium of Hydrogen Energy. http://dx.doi.org/10.1016/B978-1-78242-362-1.00007-9 Copyright © 2016 Elsevier Ltd. All rights reserved.